GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: 7/27/77

Project Title: "A Study of Lightning Transients on Buried Cables."

Project No: A-2029

Project Director: Mr. J. A. Woody

Sponsor: NASA - John F. Kennedy Space Center

Agreement Period: From 7/20/77 Until 9/19/77

Type Agreement: Contract No. NAS10-9210

Amount: $6,809 (Fixed-Price, Level of Effort)

Reports Required: Final Report

Sponsor Contact Person (s):

Technical Matters

Contractual Matters
(thru OCA)

William M. Baulig
John F. Kennedy Space Center
NASA
Procurement Office
Kennedy Space Center, FL 32899

Defense Priority Rating: None

Assigned to: Electronics Technology Laboratory (School/Laboratory)

COPIES TO:

- Project Director
- Division Chief (EES)
- School/Laboratory Director
- Dean/Director—EES
- Accounting Office
- Procurement Office
- Security Coordinator (OCA)
- Reports Coordinator (OCA)
- Library, Technical Reports Section
- Office of Computing Services
- Director, Physical Plant
- EES Information Office
- Project File (OCA)
- Project Code (GTRI)
- Other

CA–3 (3/76)

Posted
B/S

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: October 17, 1977

Project Title: A Study of Lightning Transients on Buried Cables

Project No: A-2029

Project Director: J. A. Woody

Sponsor: NASA - John F. Kennedy Space Center

Effective Termination Date: 9/19/77

Clearance of Accounting Charges: 9/19/77

Grant/Contract Closeout Actions Remaining:

Otis: Property?
NASA Form 1018?

- x Final Invoice ~~and Closing Documents~~
- _ Final Fiscal Report
- x Final Report of Inventions
- _ Govt. Property Inventory & Related Certificate
- _ Classified Material Certificate
- _ Other __________

Assigned to: Electronics Technology Laboratory (School/Laboratory)

COPIES TO:

Project Director	Library, Technical Reports Section
Division Chief (EES)	Office of Computing Services
School/Laboratory Director	Director, Physical Plant
Dean/Director—EES	EES Information Office
Accounting Office	Project File (OCA)
Procurement Office	Project Code (GTRI)
Security Coordinator (OCA) ✓	Other __________
Reports Coordinator (OCA)	

CA–4 (3/76)

A-2029

FINAL TECHNICAL REPORT

Contract NAS10-9210

INITIAL PHASE OF STUDY OF LIGHTNING TRANSIENTS ON BURIED CABLES

By

J. A. Woody

R. S. Smith

October 1977

Prepared By

Electronics Technology Laboratory
ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
Atlanta, Georgia 30332

For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHN F. KENNEDY SPACE CENTER
Kennedy Space Center, Florida 32899

PREFACE

This report was prepared within the Electronics Technology Laboratory of the Georgia Tech Engineering Experiment Station. It presents the findings of a preliminary investigation into the coupling of lightning transients to underground cables at Kennedy Space Center (KSC). This investigation represents the initial phase of a study of the techniques for measuring transients on cables and for mathematically analyzing the coupling of transients to cables. The overall objective of the study is to define the instrumentation and analysis techniques that will permit transients on cables to be correlated with, and predicted from, the occurrence of nearby lightning discharges.

This program was conducted in accordance with Contract NAS10-9210 and was under the general supervision of Mr. D. W. Robertson, Laboratory Director, and Mr. H. W. Denny, Head of the Electromagnetic Compatibility Group. Mr. J. A. Woody was the Project Director.

The authors wish to express their appreciation to Mr. William Jafferis, KSC Technical Representative, and Mr. David Perales of KSC for their support and assistance in conducting this initial investigation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Kennedy Space Center (KSC) is located in an area of very high thunderstorm activity--the average number of thunderstorm days per year is more than 80. In this area where numerous lightning discharges occur each year, a large number of direct strikes to facilities and to earth as well as indirect cloud-to-cloud discharges can be expected. Both types of discharges can induce voltage surges to any underground cables that may be nearby. At KSC, an extensive underground network of cables (signal, control, and power) exists to provide functional support for the launch facilities. On these cables, lightning-induced voltage surges can produce erroneous indications of malfunctions, resulting in unnecessary launch delays. Two needs exist to help reduce these lightning-related delays. One need is for a method to correlate surges on the underground cables with lightning discharges at KSC; another need is for a method of predicting cable surges knowing the relative location and characteristics of a particular lightning discharge.

In order to develop these correlation/prediction methods, both lightning-related information and cable data must be obtained and analyzed. The required lightning-related information includes (1) the characteristics (rise time, peak current, etc.) of lightning discharges and of transients on underground cables, and (2) techniques to locate the discharges and to analyze the coupling phenomenon. In a similar manner, the required cable data consists of the type of cables, their electrical characteristics, and their routing.

A continuing effort to define some of the lightning-related information has been underway for several years at KSC. This effort includes the development and operation of KSC lightning instrumentation: a Lightning Detection and Ranging (LDAR) system and a field mill network. The LDAR system maps the space-time history of electrical discharges in clouds by measuring the time of arrival of pulse RF emissions (30 to 50 MHz) at several widely separated antennas. The system has been modified to also provide a capability for locating and measuring cloud-to-ground lightning discharges. The field mill network utilizes numerous electrical field sensors distributed over the KSC complex to measure the electrostatic field intensities and the changes in these fields. The electric field data are analyzed and computer plots of equipotential gradient contours in the vicinity of KSC are generated.

These contours provide another method for locating cloud-to-ground lightning discharges.

In addition to the KSC lightning instrumentation effort, KSC is hosting the Thunderstorm Research International Program (TRIP) for 1976, 1977, and 1978. TRIP consists of lightning and thunderstorm studies conducted by atmospheric scientists gathered at KSC during the periods of highest lightning activity. KSC provides support for this program by operating the LDAR system and the field mill network. KSC expects to utilize the information collected by the TRIP atmospheric scientists as an aid in locating cloud-to-ground strikes and verifying the accuracy of the KSC lightning instrumentation.

As the initiation of a larger program to define the remaining lightning-related information and cable data and to develop the needed correlation/prediction techniques, the preliminary investigations described in this report were performed. These preliminary investigations consisted of a one week analysis/familiarization survey at KSC, the organization and brief analysis of the information/data obtained, and a review of a Georgia Tech developed mathematical lightning-surge coupling model. This initial investigative effort was intended to provide essential background material for the later program.

During the survey, a first-cut identification was performed of the location and type of cables that have been instrumented to measure and record transients. Discussions with various site personnel were held to obtain the approximate routing, type, and length of these specific cables. In addition, several cable plant drawings were reviewed and copies of selected drawings were obtained. Also during the survey, the specific surge instrumentation employed on the cables was identified. In each instance, the instrument manual was reviewed and the operation of the instrument was discussed with site personnel. As the final part of the survey, initial steps were taken toward defining the lightning-related data that is being, and has previously been, collected. To supplement the on-going effort at KSC, the major emphasis in defining this lightning-related data was directed toward an examination of cable transients.

Following the survey trip, the mathematical surge coupling model developed at Georgia Tech was reviewed. The input data requirements, the basic assumptions, and the limitations for this model were defined.

2. SUMMARY OF FINDINGS

2.1 Instrumented Cables

At KSC, seven representative underground signal/control lines are presently instrumented to measure and record induced transients. Each instrumented line is one pair of a miltipair cable; each cable is routed in duct banks or directly buried with other similar cables. The cables, however, are not necessarily located in the same relative position within the duct banks or in the earth through out the cable run. The routing of these cables is distributed over the KSC complex in such a manner so as to represent the routing of the majority of the existing cables. There are two basic types of lines instrumented: (1) wide-band twinaxial lines (two each) associated with the Lightning Detection and Ranging (LDAR) system and (2) twisted-pair lines (five each) associated with the field mill network. Each twinaxial line consists of an outer shield and two No. 16 AWG conductors appropriately spaced to provide a constant impedance. This shielded line and other lines are enclosed in a common lead sheath. These twinaxial lines are normally used for high speed data, video, and RF signals. Each twisted-pair line consists of two No. 19 AWG conductors and is combined with other similar pairs into a multiple conductor cable. (Some of these multiple conductor cables have overall shields and some do not.) These twisted-pair lines are normally used for slow data rate, audio, and control signals. The seven instrumented lines are not currently used for any other purpose.

(The data obtained during the survey is not sufficient to define the electrical characteristics of the cables. Information on these characteristics is required for input to the surge coupling model (see Section 2.3). Further efforts will be necessary to obtain this information prior to using the model.)

One end of each twinaxial line is terminated with a resistive load (see Section 2.2) on the primary frame at its repeater site; the other end of each line terminates in a monitoring instrument in the Central Instrumentation Facility (CIF) Operations Building. The remote (resistively loaded) end of one of the twinaxial lines is in the Vehicle Assembly Building Repeater (VABR) located northwest of the CIF Operations Building. This line is routed to the Communications Distributing and Switching Center (CDSC) in duct banks parallel to and slightly east of Kennedy Parkway (see Figure 1). From the CDSC, the line is routed to the CIF building via Manholes 002, 137, 019, 021, and 025. The line then goes through Room 161 of the CIF building to Manhole 126; from this point, the line proceeds along the west side of the access road to the CIF Operations Building. The other twinaxial line begins at the Banana River Repeater Site (BRRS) which is southeast of the CIF Operations Building as shown in Figure 2. This cable is routed from the BRRS through a duct bank along the north side of NASA Parkway. Where the Parkway becomes a divided highway, the duct bank crosses to the median and is routed to the CDSC through Manholes 003 and 002. From the CDSC to the CIF Operations Building, the routing is as described above.

In a similar manner, one end of each of the five instrumented twisted-pair lines is resistively terminated at a discontinued field mill site (former Sites 1, 3, 4, or 24). The field mills that were located at these sited have been relocated at four new sites with the same numbers. (In the following paragraphs, specific site numbers are for the discontinued field mill sites.) The resistive termination on the instrumented lines is made at a junction terminal box on the perimeter of the associated discontinued field mill site. The other end of each line is terminated in monitoring instrumentation in the Launch Control Center (LCC).

Site 1 is located at Playalinda Beach, northeast of the LCC as shown on Figure 3. The twisted-pair line from this site is in a directly buried cable which is routed along the east sides of Beach Road and Old Cape Road to the Beach Terminal Building (BTB). The line goes straight through the primary frame in the BTB and exits the building through Manhole 373. From this point, the cable passes near the northeast corner of Launch Pad 39A and along the north side of the Crawlerway through Manholes 372, 375, 364, and 350. The cable enters the northeast corner of the LCC via Manhole 419. Between the BTB and the LCC the cable is located in a duct bank.

Site 4 is located approximately 19,000 feet south of Site 1, as shown on Figure 4. From Site 4 to the LCC, the routing path is common with that of the twisted-pair line from Site 1.

Site 3 is located northwest of the LCC near Weather Tower No. 12 as shown on Figure 5. The twisted-pair line from this site is routed in a

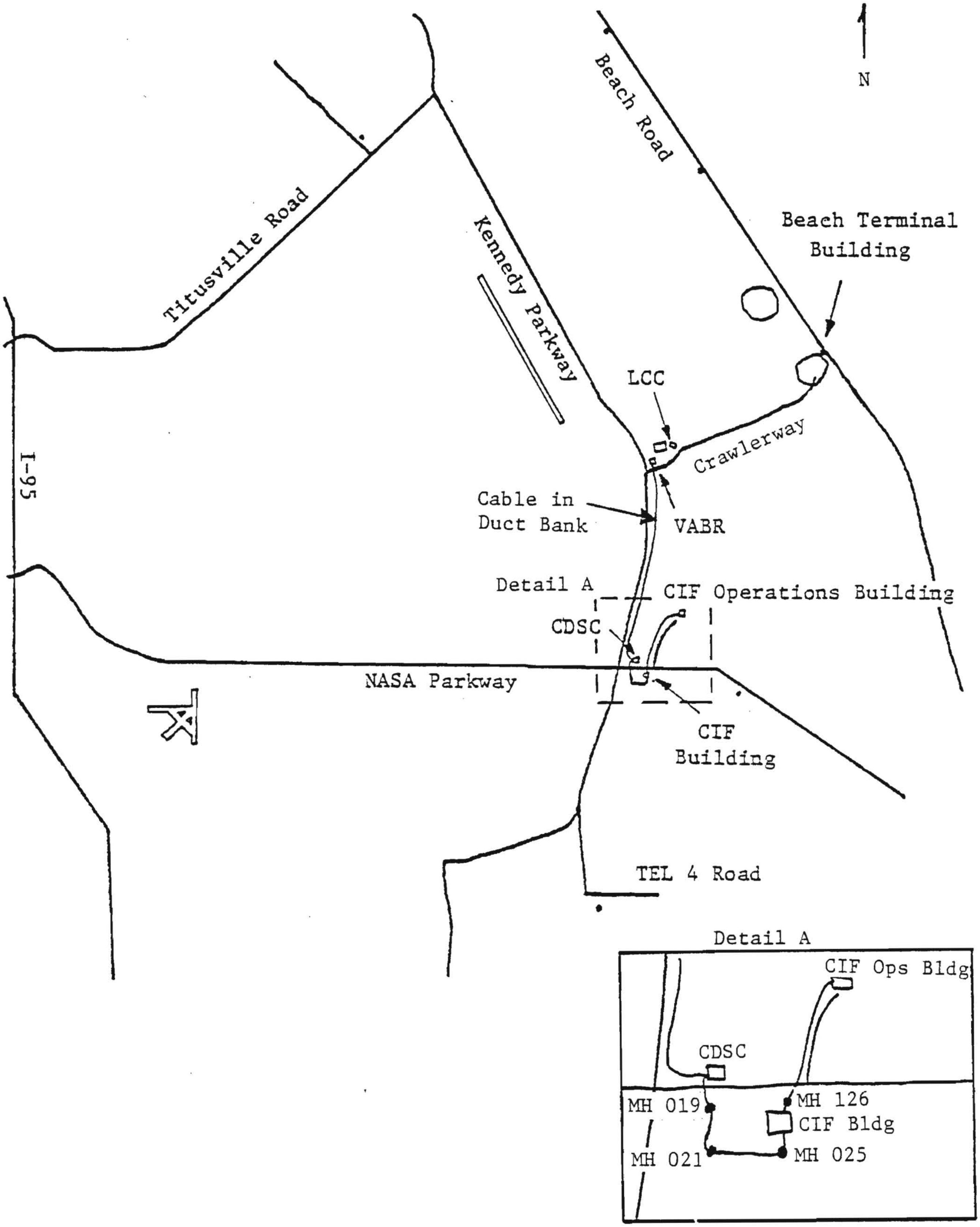

Figure 1. Routing of the Wide-Band Twinaxial Line from the VABR to the CIF Operations Building

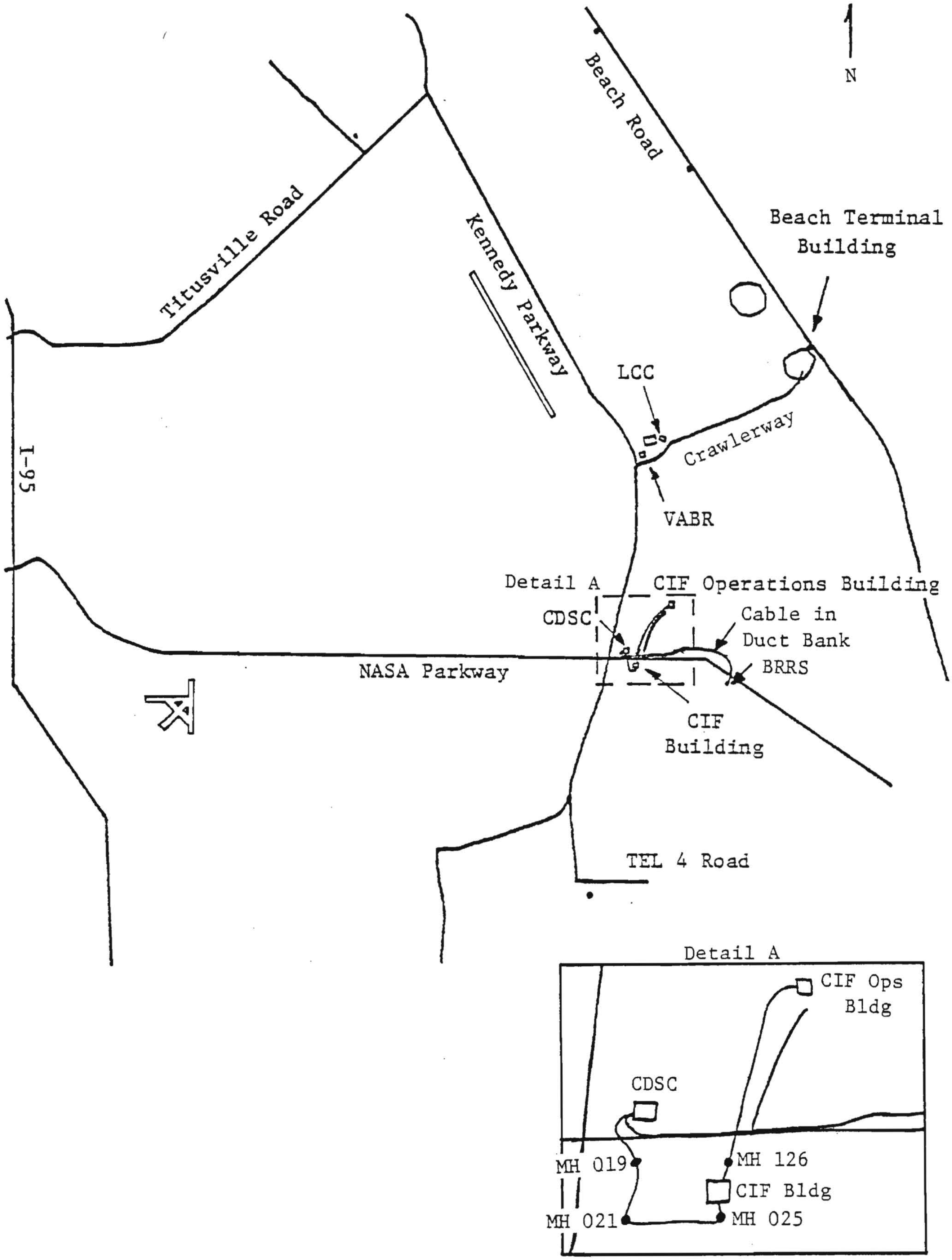

Figure 2. Routing of the Wide-Band Twinaxial Line from the BRRS to the CIF Operations Building.

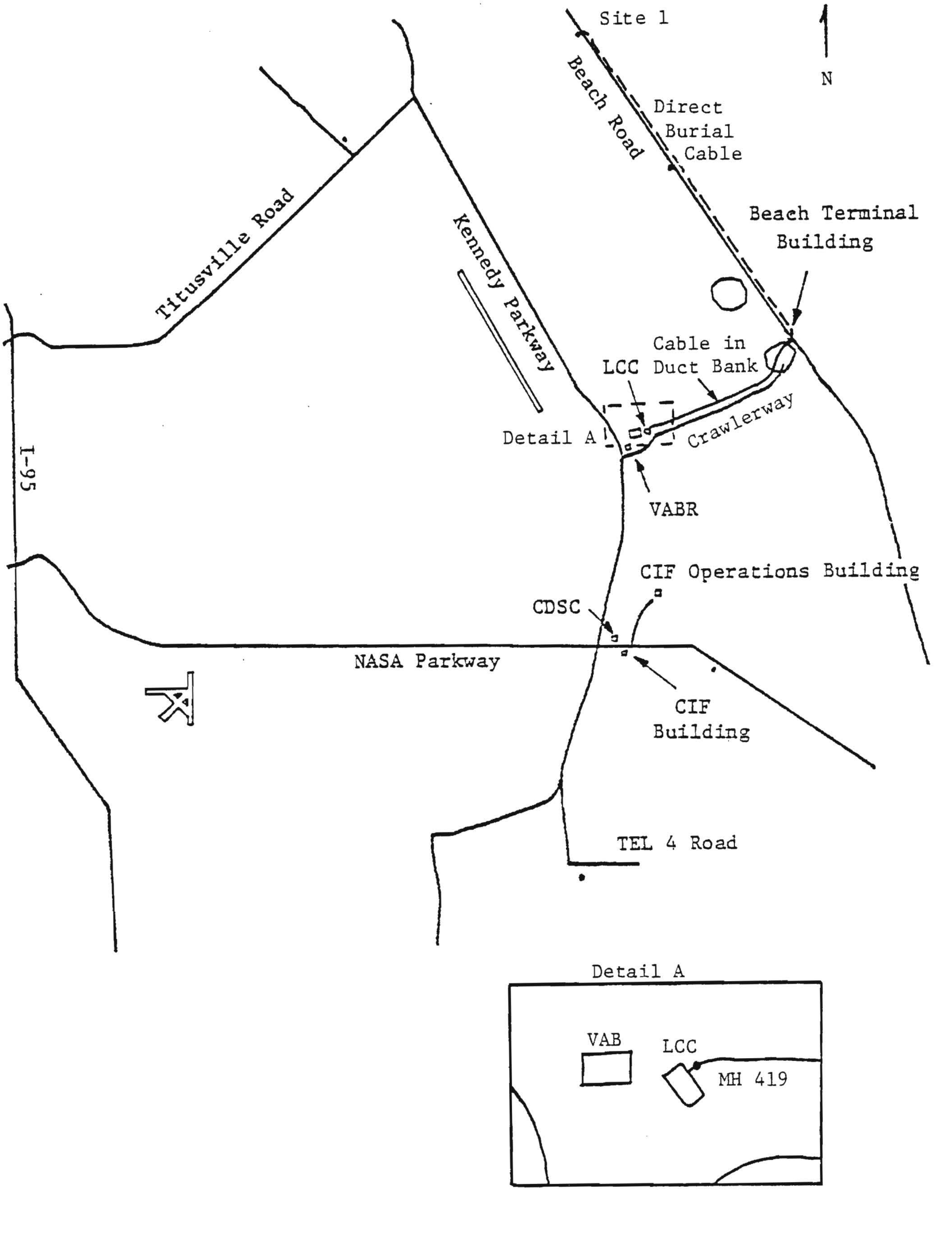

Figure 3. Routing of the Twisted-Pair Line from Old Field Mill Site 1 to LCC.

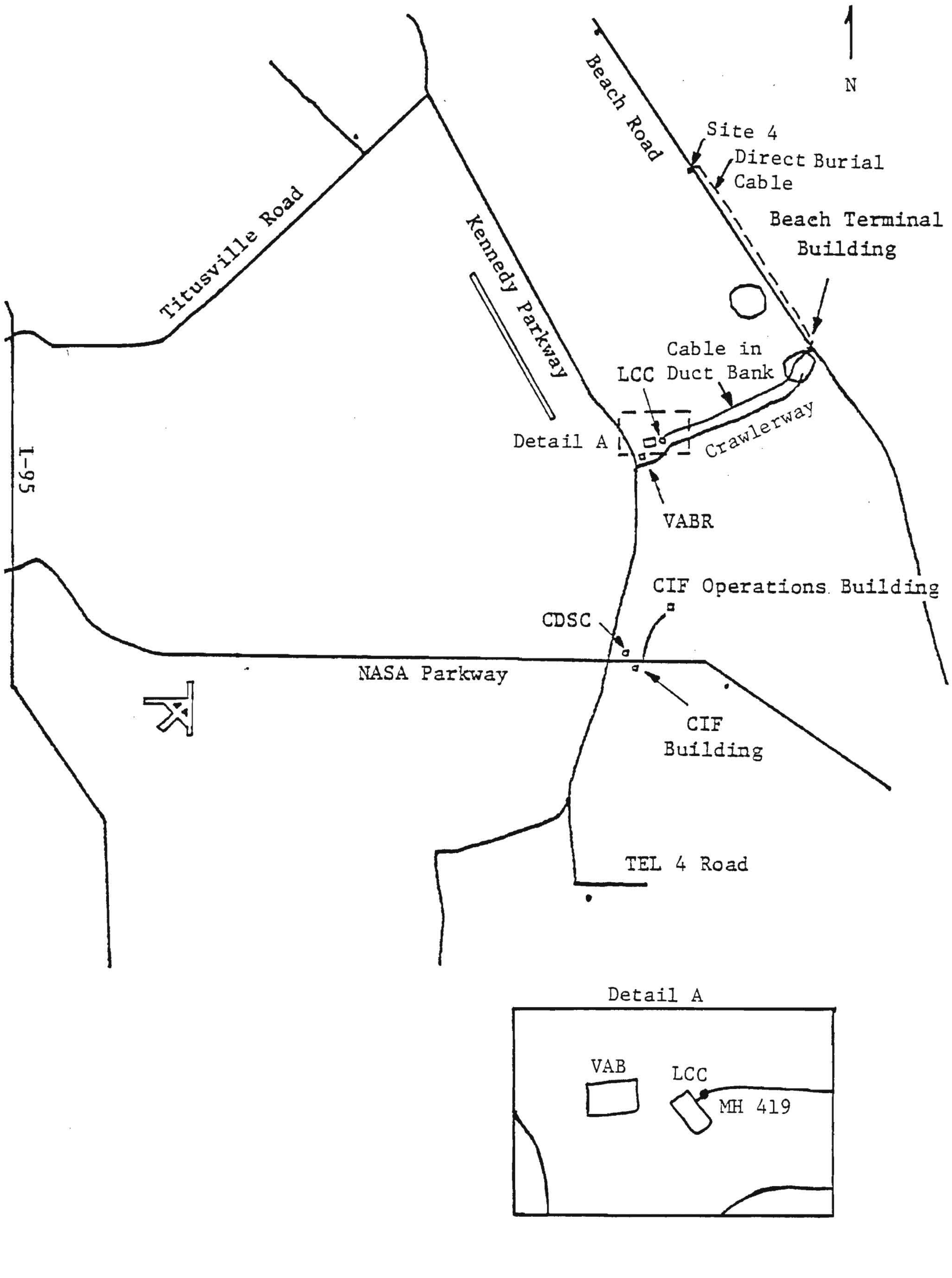

Figure 4. Routing of the Twisted-Pair Line from Old Field Mill Site 4 to LCC.

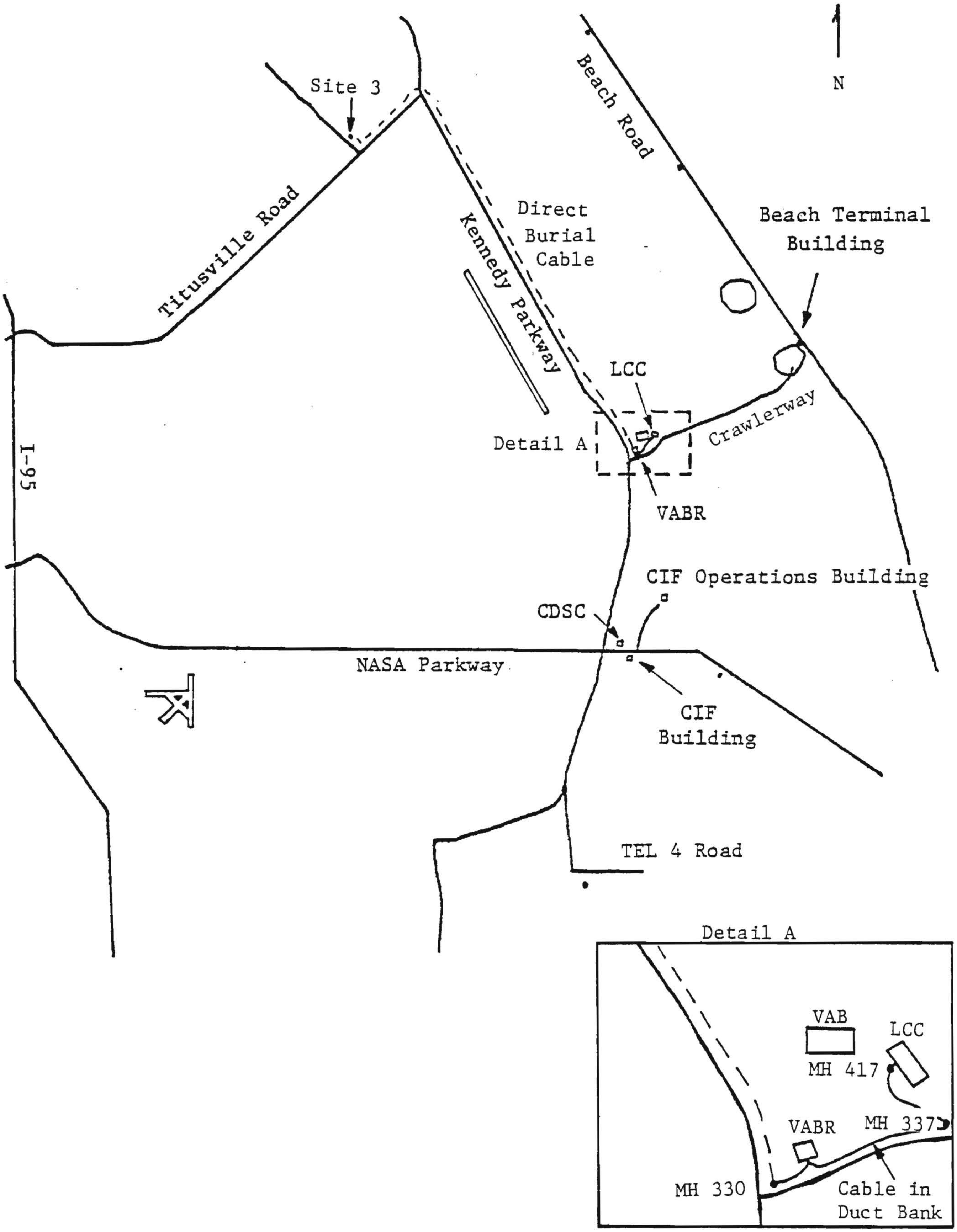

Figure 5. Routing of the Twisted-Pair Line from Old Field Mill Site 3 to LCC.

directly buried cable located on the north side of Titusville Road to Kennedy Parkway. It is then routed through Manhole 600 at Wilson's Crossing and Manhole 330 near the VABR. From Manhole 330, the cable goes through a duct bank to the primary frame in the VABR via Manhole 331. The cable is routed in a duct bank from the VABR to the northwest corner of the LCC via Manholes 331, 337, and 417.

Site 24 is located near Weather Tower No. 5, generally south of the LCC, as shown on Figure 6. Two twisted-pair lines are routed from this site to the LCC. These two lines are in cables located in a duct bank on the south and east sides of TEL 4 road to Manhole 076 at Kennedy Parkway. The duct bank is then routed along the east side of Kennedy Parkway and south side of NASA Parkway to the CDSC via Manholes 049, 044, 041, 019, 137, and 001. The twisted-pair lines go through the primary frame in the CDSC and exit in Manhole 001. The cables containing these twisted-pairs are routed in a duct bank from the CDSC to the VABR via Manholes 001, 302, 320, 330, and 331. Again, the twisted-pairs go through a primary frame in the VABR and are located in the duct bank which passes through Manholes 331, 337, and 417 to the northwest corner of the LCC.

The cables containing the twinaxial lines and twisted-pair lines include double taped armoured (DTA), stalpeth (a type of impregnated paper), and plastic insulated cables (PIC). However, the exact location of each type and its electrical characteristics was not determined. Routings of duct banks and directly buried cables appeared to be roughly parallel to roadways except as indicated. A more exact determination of cable locations can be made from Federal Electric Corporation (FEC) Drawing No. FEC/SOCA-1001 entitled "Underground Conduit Schematic and Buried Cable Area Map."

2.2 Transient Instrumentation

As noted above, recordings of the transients induced on the twinaxial lines and on the twisted-pair lines by lightning discharges are made in the CIF Operations Building and the Launch Control Center, respectively. Transients on the twinaxial lines are recorded using a digital transient recorder (Biomation Model 8100) while transients on the twisted-pair lines are recorded directly on magnetic tape.

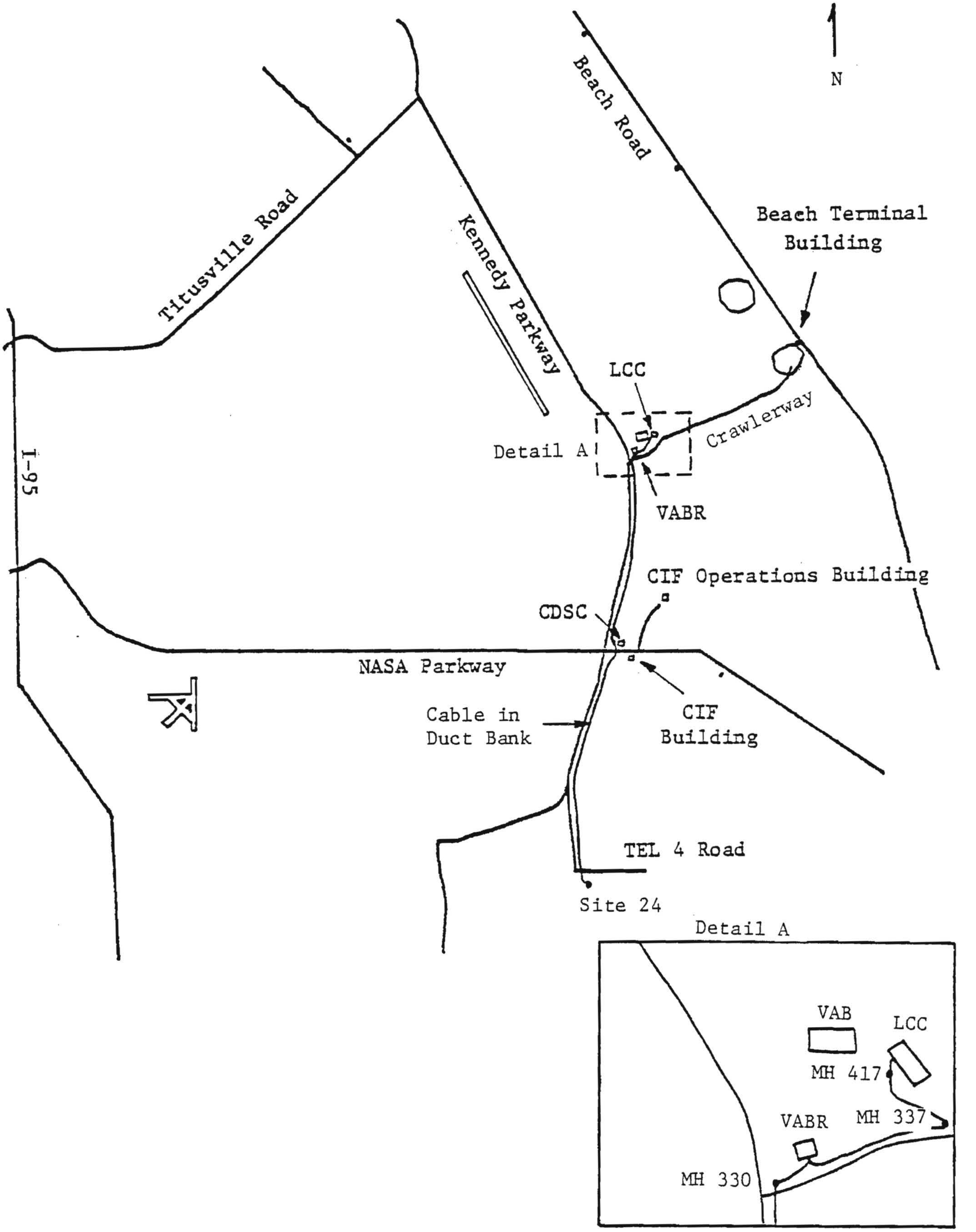

Figure 6. Routing of the Twisted-Pair Line from Old Field Mill Site 24 to LCC.

The instrumentation setup for the two twinaxial lines is shown in Figure 7. At the repeater sites (VABR and BRRS, see Figures 1 and 2), each twinaxial line is terminated with a 124-ohm resistor to represent the load that would normally be present on such a line. On the other end, 124 Ω-to-50 Ω impedance-matching transformers are connected to both lines. (The specific characteristics of these transformers were not established -- they are thought to be standard signal transformers identified as "197 coils" by KSC site personnel.) The outputs of the transformers are connected to video distribution amplifiers (Telemet Co., Model Telechrome 3200). These amplifiers have a relatively high input impedance (Z_{in} = 50k Ω) and a wide frequency response of from 10 Hz to 12 MHz (3 dB points). Their gains are adjustable from 0.5 to 1.75 with a maximum output voltage of -2 or +1.5 volts. These amplifiers were originally designed for signal distribution applications, thus they have multiple 50-ohm outputs. A peak reading voltmeter is connected to one of these outputs for monitoring the occurrence of transient signals.

One of the outputs of each distribution amplifier is fed to one channel of the Biomation recorder. The recorder stores a digital (sampled) equivalent of the transient waveform in memory. The stored representation is then used to reconstruct the analog signal for display or re-recording at a slower rate. The sample interval of the Model 8100 can be set between 0.01 μs and 10 sec. The associated maximum record time is 2048 times the sample interval. The input voltage range is adjustable from ± 50 mV to ± 5 V. Thus, very fast lightning transients with amplitudes up to 5 V can be recorded. (At the time of the survey, a 0.1 μs sample interval (205 μs total record time) and an input voltage range of ± 1 V was being used. In order to record an entire transient event, it may be necessary to use a longer total record time which can be obtained by increasing the sample interval. A further analysis of the expected amplitudes and rise and decay times of the induced transients will need to be performed before the optimum settings can be determined.)

The output of the transient recorder is connected to a magnetic tape recorder so that the captured waveforms can be permanently stored. Also, as noted previously, a second output of the distribution amplifier is

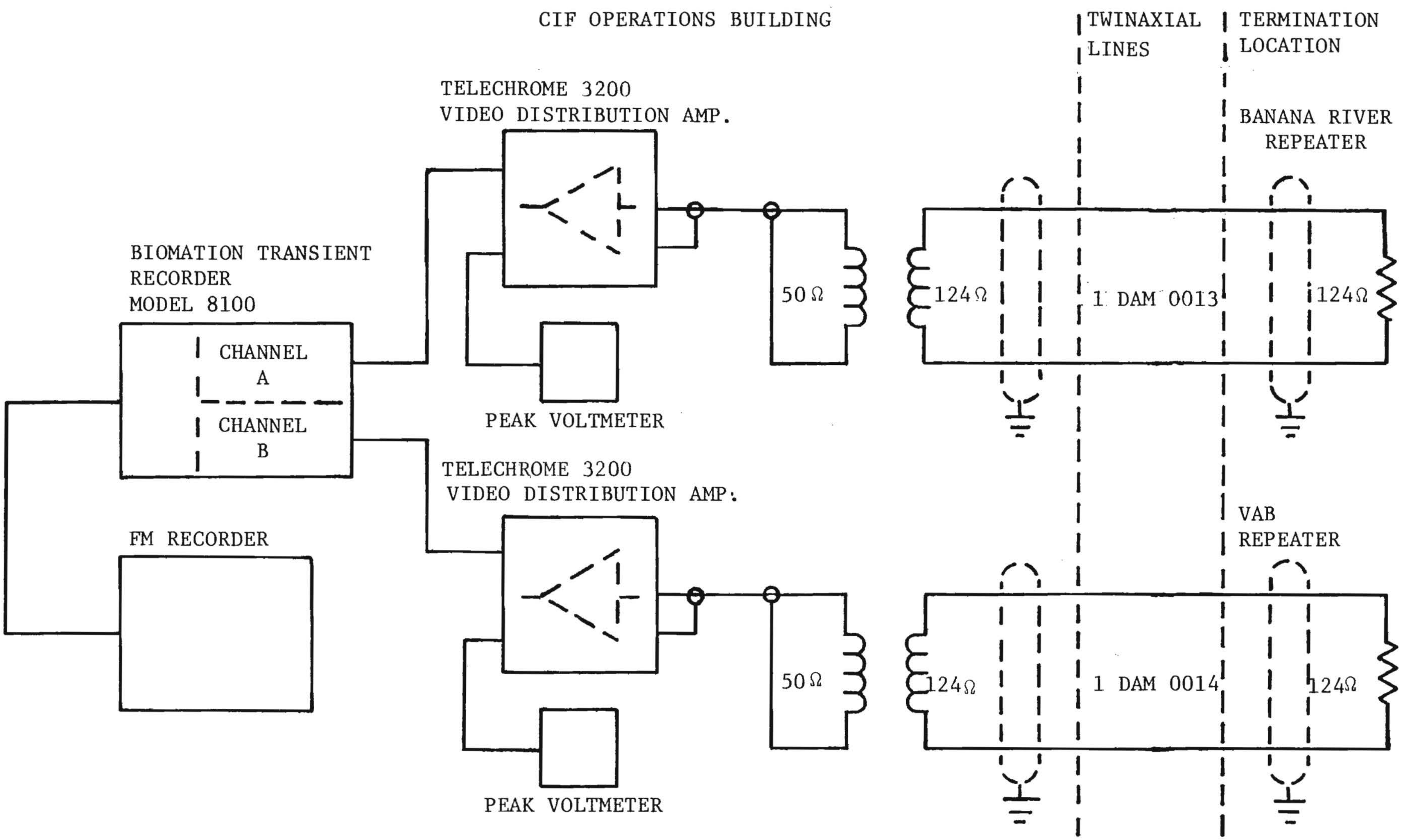

Figure 7. Configuration of Wide-Band Twinaxial Lines and Associated Measurement/Recording Instrumentation.

connected to a peak-reading voltmeter which serves as a backup for the Biomation recorder.

The five twisted-pair lines associated with the field mill network are configured to represent typical signal lines at KSC. The configurations of these lines are illustrated in Figure 8. At the (discontinued) field mill sites (see Figures 3 through 6), each twisted-pair line is terminated with a resistor of 1, 100, or 600 ohms, depending on the type line being represented. In the Launch Control Center (LCC), the other end of these five lines are terminated according to the type line being represented. As shown in Figure 8, a NEFF Instrument Corporation Model 199 differential dc amplifier is connected to each of the five lines. In addition, two of the lines (the ones to Sites No. 3 and No. 24) have NEFF amplifiers connected single-endedly to ground. These seven amplifiers serve as buffers for the terminated lines. These amplifiers have an input impedance of 100 megohms, an adjustable gain from 1 to 3000, a maximum output level of $\pm$ 10 volts, and a frequency response of 0 to 20 kHz. The gain of each amplifier is set to the maximum level that will still give a reasonably low ambient noise level. These settings are shown on Figure 8.

The output of each NEFF amplifier is fed to a channel of an Ampex Model FR 1300 magnetic tape recorder. This tape recorder typically runs at 30 inches per second which allows a bandwidth of 10 kHz to be realized. One timing track and one voice track is also available for use. For subsequent analysis of the recorded transient data, the output of the tape recorder is fed to a Honeywell Model 1612 Visicorder oscillograph. This oscillograph has a maximum practical speed of 40 inches per second and a maximum input of $\pm$ 5 volts. The oscillograph also has two timing tracks for simultaneously recording reference time codes. Thus, a permanent magnetic tape record of the transients on the five lines along with a time reference is obtained with the present setup; oscillograph copies of this data can be made when needed.

At the time of the survey, no transients had yet been recorded on the two instrumented twinaxial lines. However, a considerable quantity of transient data on the five instrumented twisted-pair lines has been recorded: over 100 20-minute tapes representing approximately 3000 feet of tape and approximately 30 hours of recording time have been obtained. A sample of the data

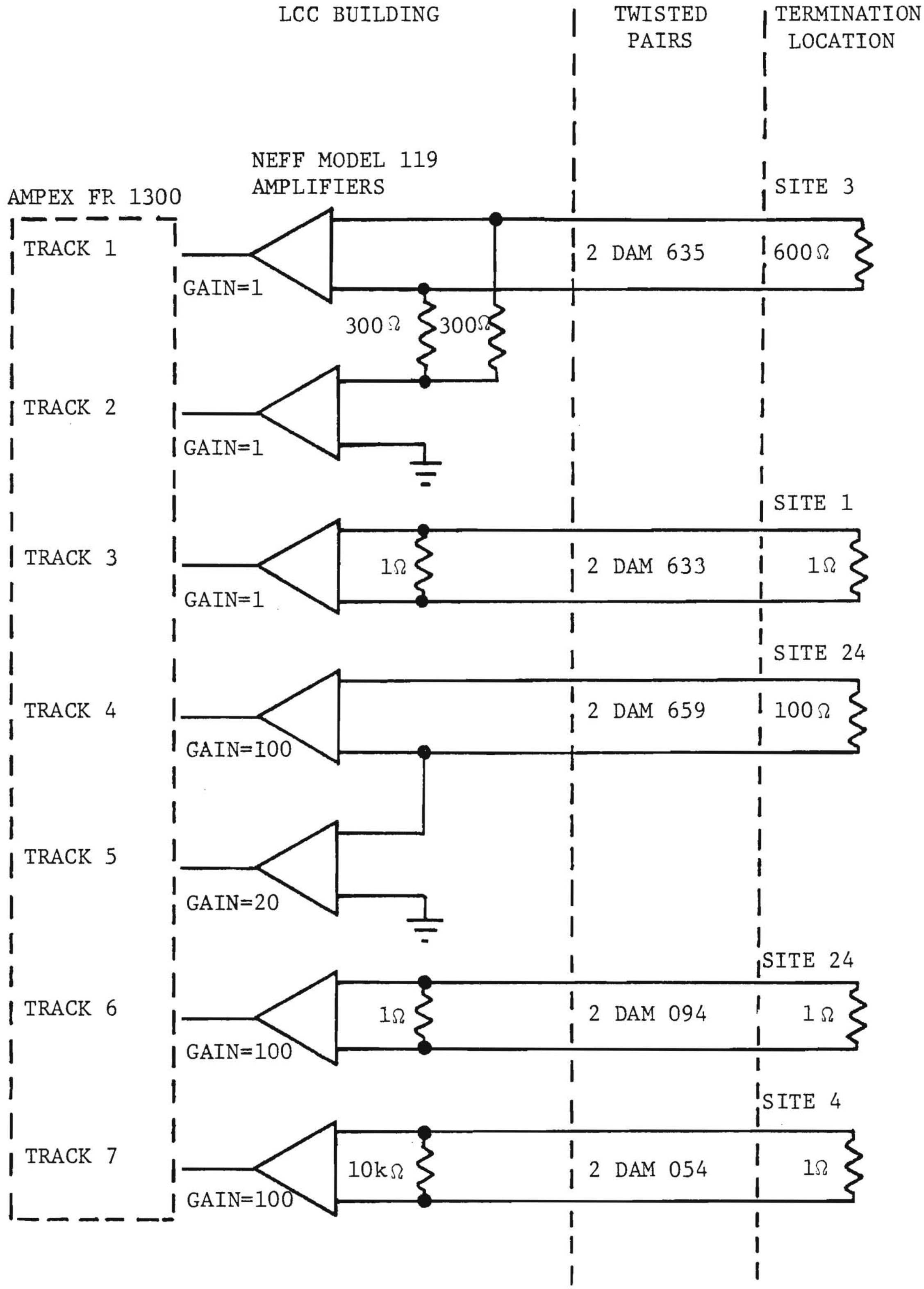

Figure 8. Configuration of Twisted-Pair Lines and Associated Measurement/ Recording Instrumentation.

from the twisted-pair lines was briefly analyzed to evaluate the resolution capabilities of the reproduction instrumentation. It appears that, with an appropriate combination of speeds on the magnetic tape recorder and the oscillograph, sufficient resolution to determine the true characteristics of the transients can be obtained. However, a more comprehensive analysis of this recorded data should be performed before a final evaluation is made. Also, the effects of frequency response and maximum amplitude characteristics of the instrumentation on the measured transient waveform should be thoroughly determined.

2.3 Surge Coupling Model

A mathematical surge coupling model for determining the lightning-induced transients on a buried coaxial cable due to earth conduction effects of nearby lightning discharges has been developed at Georgia Tech.[1,2] This model has been programmed in FORTRAN IV language for the CDC Cyber 74 computer. As presently configured, it requires approximately 1 hour of running time and a considerable amount of computer memory.

The model is used to calculate the voltage and current anywhere along the outer and center conductors of the buried coaxial cable by analyzing the coupling from a direct stroke to earth. The lightning channel is represented with a series of point dipoles positioned along the discharge path above the surface of the earth. The resulting fields and potentials in the earth are calculated from the electromagnetic field characteristics of these dipoles. These calculations yield the corresponding electric field intensity along the position of the buried cable. Then using distributed transmission line formulas, the voltage and current waves on the outermost conductor of the coaxial cable are determined from the calculated field intensity. Once the induced voltage and current surges on the outer conductor of the coaxial cable are known, the induced voltage and current surges on

1. Norgard, J. D. and Chen, C. L., "FAA Lightning Protection Study: Lightning-induced Transients on Buried Shielded Transmission Lines," Report No. FAA-RD-75-108, Contract DOT-FA72WAI-356, June 1975.

2. Norgard, J. D. and Chen, C. L., "FAA Lightning Protection Study: Lightning-induced Transients on Buried Shielded Transmission Lines: Numerical Analysis and Results," Report No. FAA-RD-77-83, Contract DOT-FA72WAI-356, May 1977.

the inner conductor are determined via the use of the impedance transfer functions for a coaxial cable. If the coaxial cable is composed of several concentric shells rather than just one, the appropriate impedance transfer functions are used recursively to obtain the voltage and current on the innermost conductor due to the voltages and currents on the outermost shield or armor.

The program used to implement the surge coupling model requires various input parameters to describe the lightning channel, the characteristics of the cable and the soil characteristics. The necessary input parameters include:

- The rise time and half-life decay times of the lightning current;
- The peak amplitude of the lightning current;
- The permeability (ε), the permittivity (μ), and the conductivity (σ) of the soil at the time the lightning discharge occurs;
- The perpendicular distance from the cable to the lightning discharge and the relative location of the discharge along the cable, i.e., the geometric configuration of the cable relative to the lightning discharge;
- The depth of burial and the length of the coaxial cable;
- The radius of each concentric shell of the cable;
- The permeability (ε), the permittivity (μ), and the conductivity (σ) of all the insulators and conductors in the cable; and
- The cable terminations.

A few of these input parameters have been or can easily be determined. For example, the characteristics of the lightning discharges can be obtained from lightning data that has been and is being recorded at KSC. Also, the relative geometric configuration of the lightning discharge and the buried cable can be defined from lightning location data taken at KSC and from the routing of cables as described in Section 2.1. Similarly, the cable terminations have been defined during the present effort (see Figures 7 and 8). A determination of the other input parameters, however, will require additional effort that must be closely coordinated with the analysis to simplify and change the model so that it applies to the existing cables at KSC.

The accuracy of the calculated induced voltages and currents on the coaxial cable depends to a large extent on the accuracy of the input parameters.

Of all the input parameters, the soil characteristics are the most critical. Small changes in σ, ε, or μ of the soil can vary the magnitude of the calculated results by a factor of 50. For the present model, this critical dependence on the characteristics of the soil may require a soil monitoring system to provide a real time update of the characteristics to the computer. However, after the model is simplified, it may be sufficient to measure the soil characteristics over a given period of time and then use the average values as input parameters. At the other extreme of parameter dependence, the distance between the lightning discharge and the buried cable is the least signigicant input parameter because the coupling is inversely proportional to the square of the distance.

To help identify the origin of voltage surges quickly and thus minimize any associated launch delays, a model capable of providing an answer in near real time (i.e. within 1-5 minutes) is needed. The model should provide at least a qualitative estimate of voltage amplitude within a short time. Further, to avoid having to compete with launch-related operations for computer time, it is desired that the surge prediction model be implemented on the minicomputers which are already used with the LDAR system and the field mill network. In order to realize the desired short response time and minicomputer compatibility, considerable simplification of the Georgia Tech model will be necessary. It may prove to be more advantageous to consider the use of other less detailed models in the interest of conserving running time and memory space.

2.4 Accuracy Requirements

The specific required measurement accuracy which will be necessary in the use of Georgia Tech's mathematical surge coupling model can not be defined until a detailed investigation of the model has been performed. This investigation is necessary to determine how the model can be changed and simplified such that it can be applied to the existing conditions at KSC. However, for some of the measurements, general comments on the required accuracy can be made. One such set of measurements are those associated with the geometric configuration of the buried cables relative to the lightning channel. This configuration is defined by measurements of the distances between any point on the cables and the location of the lightning channel. In turn, these distances are determined from the measured locations of the lightning channel and the routing of the buried cables. Thus, the accuracy of the distances between the lightning channel and the cables depends on the measurement accuracy used to locate each one. Small errors in locating either the cable or the lightning channel do not significantly affect the results of the surge coupling model since the result calculated by the model is inversely proportional to the total separation distance. The per cent error in the results for typical per cent errors in measuring the separation distance is given in Table 1. For example, if the true distance between a point on the cable and the lightning channel is 5 kilometers and the measurement errors in locating the strike and the cables are such that the true separation distance can only be determined within ± 100 meters (± 2%), then the error in the model results will be approximately 4%. This example with only 4% error assumes that the exact true value of all the other model inputs are used; errors in each of the other inputs will increase the total error.

During the investigation to simplify the model, the criticality of the various input parameters must be analyzed. First, the accuracy capabilities of state-of-the-art transient instrumentation and the accuracy of the model results necessary to correlate the measured and the predicted transients must be defined. Then the criticality of the model's various input parameters in achieving the required accuracy of the results must be considered in making simplifying assumptions for the model. Only then can the measurement accuracy of all the parameters be determined.

TABLE 1

MODEL RESULTS ERRORS FOR TYPICAL SEPARATION DISTANCE ERRORS

Per Cent Error in Total Separation Distance	Per Cent Error In Results
-20	-56.2
-10	-23.5
-5	-10.8
-3	-6.3
-2	-4.1
-1	-2.0
-0.5	-1.0
-0.25	-0.5
-0.1	-0.2
-0.01	-0.02
0	0
0.01	0.02
0.1	0.1
0.25	0.5
0.5	1.0
1	2.0
2	3.9
3	5.7
5	9.3
10	17.4
20	30.6

3. CONCLUSIONS AND RECOMMENDATIONS

As an initial phase of an effort to develop a method of correlating transients on underground cables with the locations and characteristics of known lightning discharges and to develop a method of predicting such transients, preliminary investigations of the available lightning-related data and of typical potentially susceptible underground cables were performed. The findings resulting from these investigations are presented in Section II. The following conclusions and recommendations are based on these findings:

1. The general routing of the seven instrumented lines have been determined relative to identified roads and duct banks. The lines in directly buried cables and the lines in cables routed through duct banks were identified. Before proceeding further to pinpoint cable locations precisely, it will be necessary to investigate simplification of the surge coupling model to determine the accuracy required by the model.
2. There are two basic types of instrumented underground lines at KSC: twinaxial lines and twisted-pair lines. Further work is required to define their specific characteristics, e.g., the type of shielding and the electrical properties of the shields and dielectrics.
3. The instrumented lines at KSC are configured to represent typical signal, control, and power lines. One of two types of transient instrumentation is presently employed on these lines: (1) a Biomation Transient Recorder on the wide-band twinaxial lines; and (2) a NEFF differential amplifier on the twisted-pair lines. An additional review of the state-of-the-art instrumentation for measuring lightning transients and approaches for monitoring these transients should be performed to provide a basis for analyzing the existing instrumentation. For example, the frequency response of the NEFF differential amplifier is probably so low as to cause distortion of the lightning transient waveform. A review of existing monitoring techniques is needed, however, before the required frequency response can be determined. Also, an investigation of the expected amplitude and rise and decay time

characteristics must be conducted before the optimum amplitude and frequency response of the instrumentation is defined.

4. During this initial phase, the amplitude and frequency response characteristics of most of the instrumentation was defined. However, the characteristics of some of the equipment still needs defining. This equipment requiring additional examination includes (1) the impedance-matching transformers, (2) the peak-reading voltmeters, and (3) the magnetic tape recorders used with the wide-band twinaxial lines.

5. Data has not been recorded from the instrumentation on the wide-band twinaxial lines; however, numerous magnetic tapes have been recorded with measurement results from the twisted-pair lines. In fact, the instrumentation on the twisted-pair lines is activated when the KSC Weather Bureau reports a storm in the vicinity. This practice results in numerous magnetic tapes that may, or may not, have any relevant lightning transient data. A more practical and economical approach may be to only activate this instrumentation when data from other lightning prediction/location instrumentation such as the field mill network indicates that the possibility of a lightning discharge is eminent. Admittedly, such a procedure will require a subjective evaluation of when to activate the instrumentation, but it may save a considerable amount of magnetic tape. A comprehensive analysis of all the data recorded to date should be performed.

6. The required input parameters to Georgia Tech's mathematical surge coupling model have been defined in Section 2.3. Some of these parameters can be determined from the findings during this initial phase or from these findings in conjunction with data from existing lightning location techniques and data from the Thunderstorm Research International Program (TRIP). For example, the cable terminations and the overall length of each cable were defined during this initial phase. The relative distance between the lightning discharge and the underground cables can be determined from the measured location of the discharge and the identified routing of the cables. Also, the characteristics of the lightning

channel can be defined from TRIP data. Further effort is necessary, however, to determine the values of the other required input parameters such as the characteristics of the cables, the characteristics of the soil, the number of straight line segments needed to represent each cable, and the length of each straight line segment.

7. Georgia Tech's surge coupling model was developed to be used for simple buried straight coaxial cables. The instrumented cables at KSC are twinaxial and twisted-pairs routed along a combination of curved paths. The model as it presently exists does not appear amenable to performing the desired near real time analysis on minicomputers at KSC. Investigations should be performed to determine ways to incorporate the other cable types and ways to reduce the running time and memory requirements. For example, one approach to reducing these requirements would be to make simplifying assumptions about the input parameters and/or the analysis techniques. In conjunction with these investigations, a review of other existing, simpler surge coupling analysis techniques should be performed to determine their relative usability.
8. The measurement accuracy requirements necessary in using any surge coupling model will depend to a large extent on the assumptions used in the model. Therefore, determination of the accuracy requirements should be accomplished after simplifying assumptions for the specific surge coupling model have been defined.